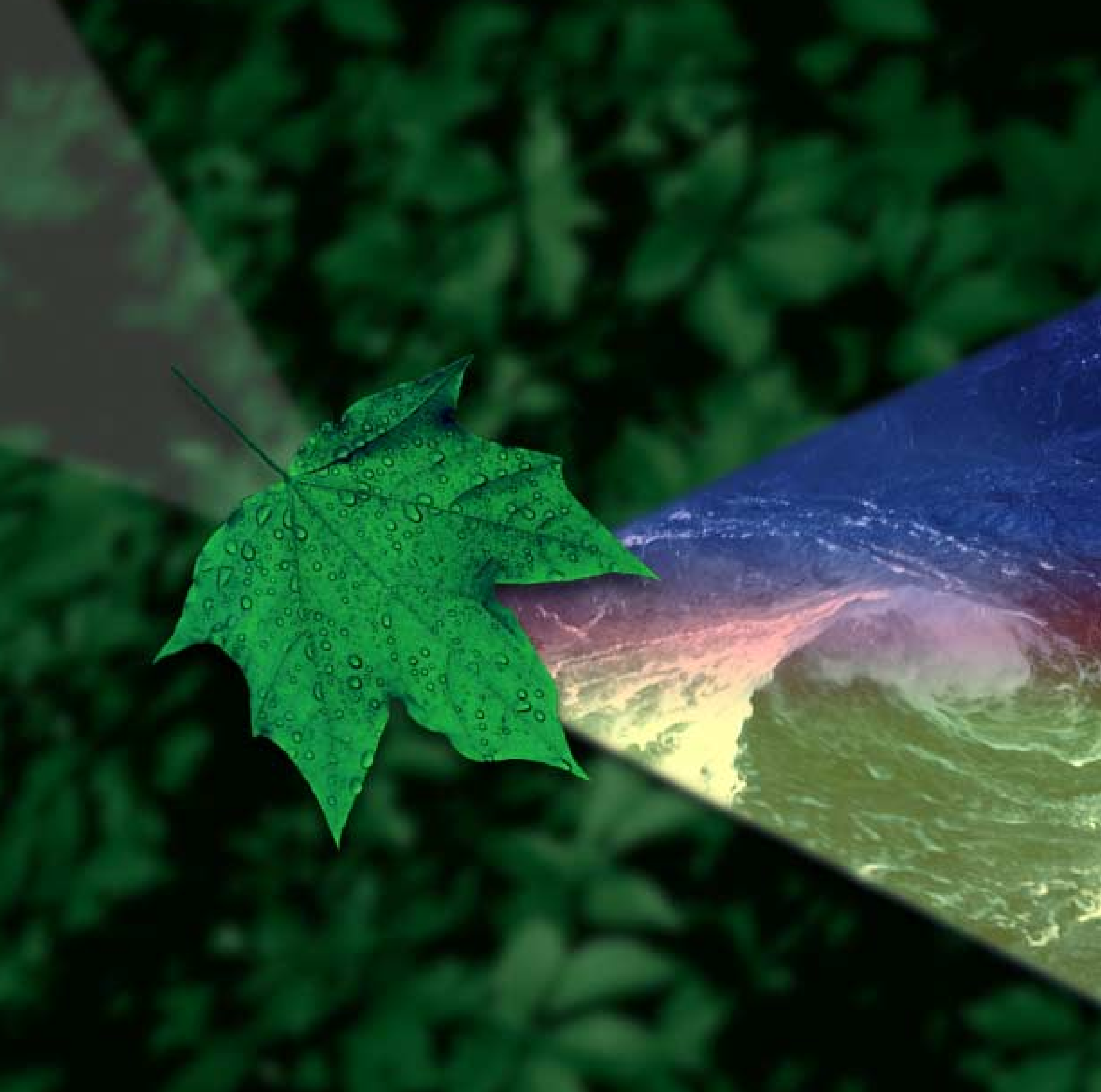
CARBON SEQUESTRATION



ADDRESSING GLOBAL CLIMATE CHANGE

Introduction

Program Areas

- Separation and Capture
- Sequestration in Geologic Formations
- Ocean Sequestration
- Terrestrial Sequestration
- Advanced Concepts
- Modeling and Assessments

The potential impact of increasing greenhouse gases in the atmosphere will be a global concern well into the 21st century.

Predictions of global energy use in the next century suggest a continued increase in carbon emissions and rising concentrations of carbon dioxide (CO_2) in the atmosphere unless major changes are made in the way we produce and use energy, in particular, how we manage carbon.

In order to stabilize and ultimately reduce concentrations of this greenhouse gas, it will be necessary to employ carbon sequestration — carbon capture, separation, and storage or reuse. Carbon sequestration, along with reduced carbon content of fuels and improved efficiency of energy production and use, must play major roles if the Nation is to enjoy the economic and energy security benefits which fossil fuels bring to the energy mix.

The President's Committee of Advisors on Science and Technology (PCAST) underscored the importance of carbon sequestration in two separate reports (issued November 1997 and June 1999). PCAST recommended increasing the U.S. Department of Energy's (DOE) research and development (R&D) for carbon sequestration. Specifically, the report stated that "a much larger science-based CO_2 sequestration program should be developed. The aim should be to provide a science-based assessment of the prospects and costs of CO_2 sequestration. This is very high-risk, long-term R&D that will not be undertaken by industry alone without strong incentives or regulations, although industry experience and capabilities will be very useful."

The peer-reviewed Office of Fossil Energy and Office of Science December 1999 report, *Carbon Sequestration: State of the Science,* assessed "key areas for research and development that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions."

To be successful, the techniques and practices to sequester carbon must meet the following requirements: (1) be effective and cost-competitive; (2) provide stable, long-term storage; and (3) be environmentally benign. Using present technology, estimates of sequestration costs are in the range of $100–300/ton of carbon emissions avoided. The goal of the program is to reduce the cost of carbon sequestration to $10 or less per net ton of carbon emissions avoided by 2015. Achieving this goal would save the United States trillions of dollars. Further, achieving a mid-point stabilization scenario (e.g., 550 ppm CO_2) would not require wholesale introduction of zero emission systems in the near term. This would allow time to develop cost-effective technology over the next 10–15 years that could be deployed for new capacity and capital stock replacement capacity.

The program portfolio covers the entire carbon sequestration "life cycle" of capture, separation, transportation, and storage or reuse, as well as research needs for two other energy-related greenhouse gases of concern, methane (CH_4) and nitrous oxides (N_2O). Specifically, the R&D program has six program areas:

- Cost-effective CO_2 capture and separation processes.
- CO_2 sequestration in geological formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.
- Direct injection of CO_2 into the deep ocean and perhaps stimulation of phytoplankton growth.
- Improved full life-cycle carbon uptake of terrestrial ecosystems.
- Advanced chemical, biological, and decarbonization concepts.
- Models and assessments of cost, risks, and potential of carbon sequestration technologies.

Drivers

Global climate change. Burning coal, oil, and natural gas to heat homes, power cars, and illuminate cities produces carbon dioxide and other greenhouse gases as by-products. Deforestation and clearing of land for agriculture also allows the release of significant quantities of such gases.

The concentration of CO_2 in the atmosphere is rising and, due to growing concern about its effects, the United States and 160 other countries ratified the Rio Mandate, which calls for "...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

Net increases in CO_2 emissions from energy systems and other human activity may be causing changes in the earth's climate, changes that in the future could be harmful to human health and global economic prosperity. Much uncertainty is associated with the global climate change issue, but it is possible, even likely, that deep cuts in net CO_2 emissions from human activity will be required over the next 50–100 years.

Growing energy demand. Today, emissions of CO_2 into the atmosphere are an inherent part of electricity generation, transportation, and building systems. The energy sector is responsible for roughly 90 percent of U.S. greenhouse gas emissions, and 85 percent of the current U.S. energy system is based on fossil fuels. Moreover, even though the use of zero-carbon fuels is expected to grow substantially in the coming decades, there are economic and environmental limits on nuclear and renewable-based energy technologies.

The challenge of global climate change also requires that we look out beyond our borders. Electricity is the fastest growing segment of the global energy market. Some have predicted that, by 2050, the forces of population growth, urbanization, expanding global commerce, and simple human aspirations could result in the global consumption of electric power that is four times greater than today.

Carbon management strategies. To date, climate change strategies have emphasized energy efficiency and the greater use of lower carbon fuels — both promising options. However, global climate change is a long-term issue, and so too will be its solution. Changing the energy system that has largely been responsible for the Nation's economic growth and prosperity — particularly changing the system overnight — is neither economically feasible nor socially responsible. Premature retirement of existing infrastructure would be prohibitively expensive and economically unwise.

Sequestration approaches have the potential to save hundreds of millions of dollars a year compared to other carbon management approaches. Sequestration also would allow continued use of much of the Nation's current energy infrastructure.

Expanding markets for carbon management technology. If the promise of sequestration is realized, a truly global market for carbon management technologies will emerge. Perhaps more important, widespread use of these technologies could significantly alter the environment. The United States needs to improve its participation in the research involved in carbon management so that, at a minimum, the United States would have its own independent capability to assess the viability, efficacy, and safety of any non-U.S. actions, such as sequestering CO_2 in the ocean. The United States will need to selectively cooperate and compete with other nations in developing these technologies, because the U.S. does not currently hold the leadership position in many key aspects of carbon management. For example, the Japanese budget in CO_2 capture and disposal appears to be 35–70 times as large as that of the United States. Moreover, various other nations (including Japan and some European nations) are leading the U.S. in the development of certain technologies and the understanding of certain phenomenon that are fundamental to implementing CO_2 capture and disposal methods.

Carbon Sequestration Program Benefits

National Benefits

- Results in an estimated cumulative benefit to the U.S. economy of $2.4 trillion through 2050;
- Provides for energy security by enabling use of vast domestic coal resources, which are expected to provide at least 50 percent of the electricity produced well into the 21st century; and
- Eases the economic transition to a sustainable climate.

Supplier Benefits

- Enables U.S. industry to establish a leadership position in a new global market for a novel class of technologies;
- Removes a major concern relative to the continued operation of existing fossil fuel plants;
- Provides flexibility to power producers by enabling the use of indigenous fossil fuels for new generation capacity; and
- Expands business opportunities for power producers by adding a commodity to the product slate.

Customer Benefits

- Keeps energy prices low by allowing continued use of low-cost indigenous fossil fuel resources; and
- Provides insurance against potential adverse environmental consequences associated with global climate change.

Accomplishments

Promoting a new area of technical endeavor, such as carbon sequestration, is a process of collection and maturation of innovative ideas.

Given the federal government's role in supporting high-risk R&D in the long-term national interest, a carbon sequestration research and technology development program is being expanded significantly on the eventuality that such technology will be needed in the energy marketplace some time in the first quarter of this century.

Since the program's inception in 1998, the Carbon Sequestration program has conducted stakeholder workshops, roadmapping exercises, and portfolio analysis leading up to its first solicitation for projects in 1998. This solicitation resulted in 12 exploratory studies to evaluate the feasibility of various sequestration technologies. Six of the 12 studies were given additional government funding in 1999 for further project development. A second solicitation in late 1999 has generated two phases of sequestration research. Phase I research projects emphasize both National Laboratory/private sector partnerships, and private sector research teams. Eight National Laboratory/private sector partnership projects were selected in February 2000. More recently, DOE selected 13 new private sector research projects from more than 60 submitted concepts.

DOE's main achievements in carbon sequestration have been in its ability to integrate industrial participation, address environmental issues, and gain support for an expanded federal sequestration program. To date, research has concentrated largely on early exploratory ventures funded primarily with federal dollars. The more recent private sector projects, however, are larger-scale partnerships with private research institutions, industries, and universities contributing an average of 40 percent of the total costs — well above DOE's minimum requirement of 20 percent.

Inter- and Intra-Agency Crosscutting Coordination

The Carbon Sequestration program has built an extensive collaborative network of relationships with private and public sector stakeholders. Within DOE, the program builds on a cooperative effort between FE and the Office of Science that has already resulted in the December 1999 peer-reviewed joint report, *Carbon Sequestration: State of the Science* and a subsequent public/industry workshop. The research pathways defined in these efforts form the structure of the program.

Within FE, the program will work synergistically with the Vision 21 Program to jointly address the three basic options to reduce CO_2 concentrations: (1) improve the efficiency of energy production and end use; (2) reduce the carbon content of fuels; and (3) carbon sequestration. For the critical area of CO_2 capture and separation, the program has important linkages with the Innovations for Existing Plants program area within the Central Systems program. In particular, the potential of integrating CO_2 control with other emissions control systems would provide the option of integrated control at a lower cost.

In the area of terrestrial sequestration, which encompasses forestry and enhanced storage in soils and vegetation, FE is working closely with the U.S. Forest Service and the Office of Surface Mining and has established Interagency Agreements with them to cooperate and partner in areas of mutual interest. In the area of geologic sequestration, FE and the U.S. Geologic Survey have a long-standing history of cooperation and collaboration. As the program proceeds, similar collaborative agreements will be sought with other federal agencies, as well as with state agencies and their representative organizations.

The program has established highly synergistic relationships with industry and academic stakeholders. These relationships started with a government/industry/academia workshop hosted by the Massachusetts Institute of Technology in 1998, and include recent activities such as a joint FE/industry/international workshop in geologic sequestration and the selection of cost-shared industry/academic/National Laboratory R&D projects through competitive solicitations. The program combines these activities with international collaboration, including joint work with the International Energy Agency's Greenhouse Gas R&D Programme and its member countries.

ACTIVITIES

Carbon sequestration enables the use of fossil fuels in energy systems without emissions of CO_2 into the atmosphere.

The program goal is to reduce the cost of carbon sequestration to $10 or less per net ton of carbon emissions avoided by 2015. Since initiation of the program in 1998, outreach and planning exercises have been conducted to help determine the appropriate direction and focus of the R&D activities.

The roadmap on page 5-7 identifies major milestones for the Carbon Sequestration program. In the program R&D portfolio, each project falls in a typical progression of R&D, where the carbon sequestration R&D stages are defined as:

– *Assessment:* conceptual designs, modeling analysis

– *Conceptual R&D:* experimental studies, prototype development

– *Bench-Scale Technology Development:* laboratory experiments, systems integration

– *Field Testing:* large-scale prototype development

– *Verification with Large Projects:* testing and monitoring during operation over extended periods of time

The near-term program will examine and identify a spectrum of science-based sequestration approaches that have the greatest potential to yield the cost-effective technologies that are required.

Separation and Capture. Current activities include: (1) development of a high-temperature membrane that can separate CO_2 from gases formed when coal is reacted with steam and oxygen in a coal gasifier; (2) development of a low-cost way to separate CO_2 from the flue gas of existing fossil fuel combustion plants with a reusable sodium-based chemical; (3) demonstration of methane capture from landfills; (4) development of an inorganic, palladium-based membrane that will separate hydrogen and concentrated CO_2 from hydrocarbon fuels; (5) study of a CO_2 separation system for a power plant that uses iron- and copper-based sorbents; and (6) the study of hydrates in the removal of CO_2 from gas streams

Sequestration in Geologic Formations. R&D is focused on: (1) using enhanced coal-bed methane recovery technology to test the viability of storing CO_2 in coals seams; (2) using a nuclear magnetic resonance well-logging technique to identify the most suitable geologic formation for long-term CO_2 storage; (3) the study of deep saline reservoirs in the Colorado and Rocky Mountain region to determine how much CO_2 can be stored and associated environmental risks; (4) identification of storage sites for mass CO_2 sequestration; and (5) evaluation of geologic and geochemical processes that could be used to sequester CO_2 into deep aquifers.

Ocean Sequestration. Current DOE/industry R&D includes: (1) the use of a combination of remotely operated deep sea vehicle technology, time lapse photography, and other analytical techniques to determine the long-term fate of CO_2 injected into the ocean; (2) large-scale CO_2 transportation and deep ocean sequestration; and (3) direct analysis of frozen CO_2 deposits (known as hydrates) on the sea floor.

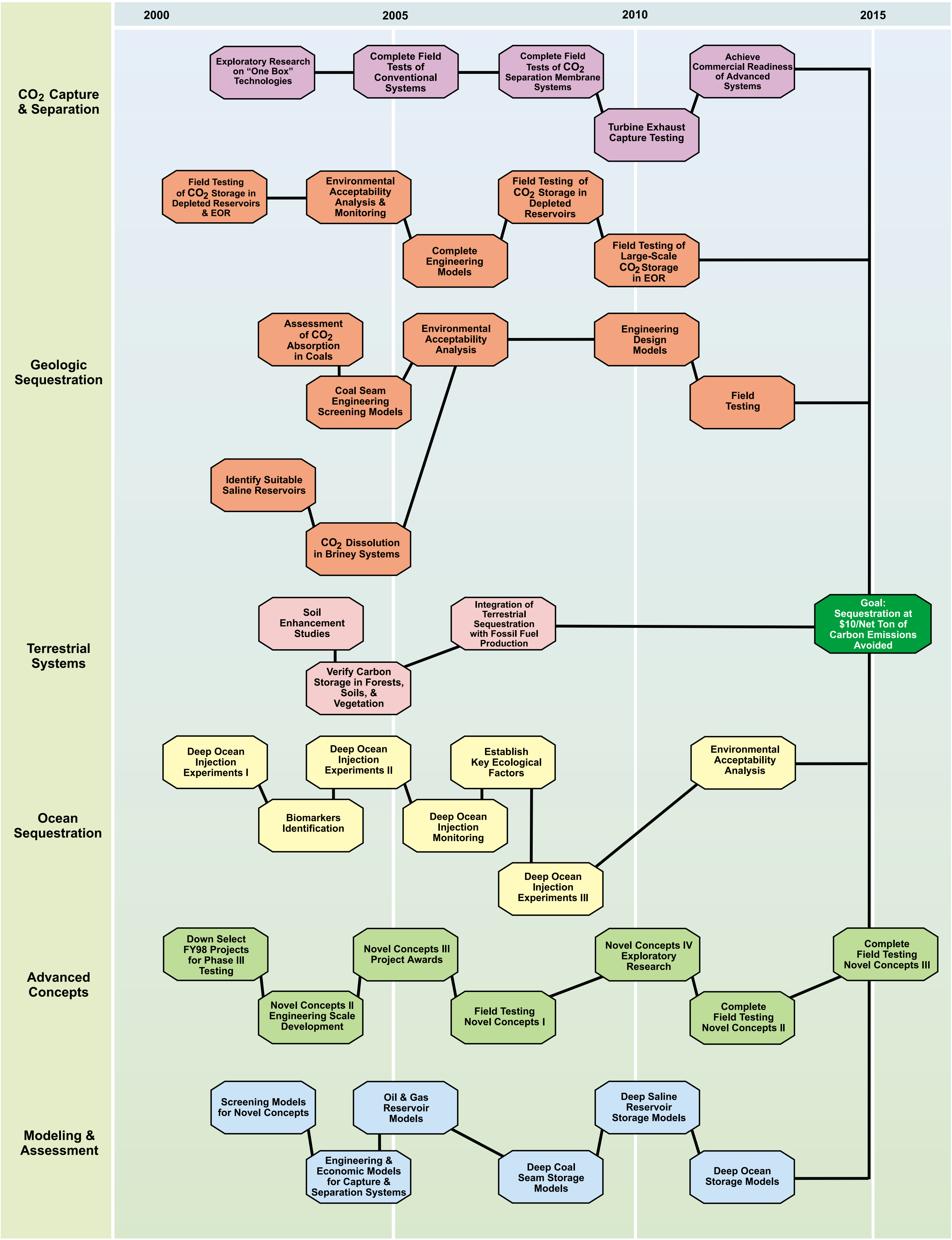
Terrestrial sequestration. Studies in this program area include evaluation of a reclamation/reforestation program that would sequester carbon in trees on abandoned mine lands in the Appalachian region and development of a system for trading carbon credits to lower the costs of CO_2 terrestrial sequestration.

Advanced Concepts. Advanced concepts R&D is focused on: (1) enhancing photosynthesis by attaching photosynthetic organisms to specially designed growths arranged in a "bioreactor," with special lighting to enhance the rate of CO_2 conversion; and (2) development of technologies that use selected species of micro-algae to photosynthesize CO_2 from power plant exhaust gases.

Modeling and Assessments. Current research in the Modeling and Assessments program area centers on: (1) development of a state-of-the-art computer model to assess CO_2 sequestration options and costs from the local to national level; and (2) development of a digital database that catalogs CO_2 source-to-sequestration site information in five midwestern states.

In the midterm, sequestration pilot testing will develop options for direct and indirect sequestration. In the long term, the technology products will be more revolutionary and rely less on site-specific or application-specific factors to ensure economic viability.

Carbon Sequestration Roadmap



OVERVIEW

Drivers

- Climate change and policies to address it may be the most influential consideration in energy use in the United States early in this century.
- Emission of CO_2 into the atmosphere is inherent to the use of fossil energy resources for electricity generation, transportation, industrial heat and power, and building systems.
- Fossil fuel's share of the domestic energy market will increase from 85 percent in 1995 to 90 percent in 2020, reflecting the abundance of the energy resource and the economic environmental limits on nuclear and renewable alternatives.
- Increased concentrations of CO_2 in the atmosphere due to carbon emissions are expected unless energy systems reduce carbon load.
- Carbon sequestration (carbon capture, separation, and storage or reuse) must: be effective and cost-competitive; provide stable, long-term storage; and be environmentally benign.
- The growing global market for carbon management technologies demands early action on the part of the United States in achieving a leadership position in the development of revolutionary sequestration technologies.

Objectives

- Provide economically competitive and environmentally safe options to offset all projected growth in baseline emissions of greenhouse gases by the U.S. after 2010 with offsets starting in 2015.
- Achieve the long-term cost goal of approximately $10/ton of avoided net costs for carbon sequestration by 2015.
- Offset at least one-half of the required reduction in global greenhouse gases, measured as the difference in a business-as-usual baseline and a strategy to stabilize concentration at 550 ppm CO_2, beginning in 2025.

Strategies

- Pursue evolutionary improvements in existing CO_2 capture systems and explore revolutionary new capture and sequestration concepts with a view toward significant cost reductions.
- Conduct fundamental studies and field tests to measure the degree to which CO_2 stays sequestered in geologic formations, including oil and gas reservoirs, coal beds and saline formations, and assess the long-term ecological impacts.
- Develop a better understanding of the ecological impacts of ocean fertilization and deep ocean direct injection of CO_2.
- Pursue integrated measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmland and forests, with fossil fuel production and use.
- Develop novel and advanced concepts using chemical, biological, and other approaches to capture, store, and reuse CO_2 from energy production and utilization systems.
- Develop assessment capabilities and analytical tools to assist in the selection of the most promising R&D efforts that have high potential, but significant uncertainties associated with their cost and effectiveness.
- Continue collaboration activities and workshops to keep all stakeholder groups — industry, end-users, non-profit organizations, academia, National Laboratories, the environmental community, and governments — apprised of new developments and maintain an open dialogue on the merits of carbon sequestration.

Performance Goals

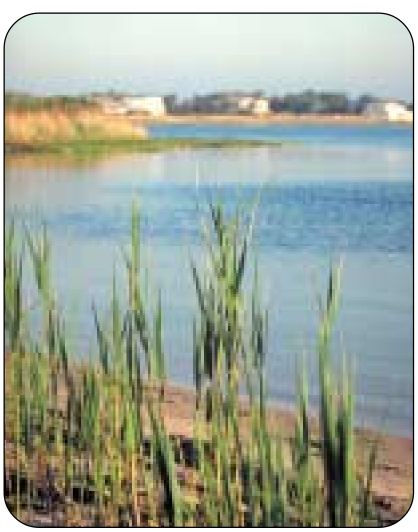
- Reduce the cost of carbon sequestration from \$100–\$300/ton today to \$10 per net ton of carbon emission avoided by 2015.
- Develop options for “value added” sequestration with multiple benefits such as using CO_2 in enhanced oil recovery operations and in methane production from deep unmineable coal seams by 2010.
- Establish the viability of larger capacity sequestration approaches suitable for deployment by industry in the post-2015 timeframe.

Separation and Capture

The goal of CO_2 separation and capture is to isolate carbon from its many sources in a form suitable for transport and sequestration.

Before CO_2 gas can be sequestered from point sources, it must be captured as a relatively pure gas. Carbon dioxide is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, hydrogen production, and limestone calcination. At least one coal-fired power plant is currently capturing and separating CO_2 and subsequently trucking the CO_2 for food processing use. However, existing capture technologies are not cost-effective when considered in the context of CO_2 sequestration. Carbon dioxide capture is generally estimated to represent three-fourths of the total cost of carbon capture, storage, transport, and sequestration systems.

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO_2 capture and separation technologies.



Several innovative schemes have been proposed that could significantly reduce CO_2 capture costs, compared to conventional processes. "One box" concepts that combine CO_2 capture with reduction of criteria-pollutant emissions will be explored.

The program area will pursue evolutionary improvements in existing CO_2 capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO_2 separation and capture are discussed below.

Absorption

Carbon dioxide can be removed from gas streams by physical or chemical absorption. Physical absorption processes are temperature and pressure dependent with absorption occurring at high temperatures and low pressures. Chemical absorption is preferred for low to moderate CO_2 partial pressures. Because CO_2 is an acid gas, chemical absorption of CO_2 from gaseous streams such as flue gas depends on acid-base neutralization reactions using basic solvents.

Adsorption

Selective separation of CO_2 may be achieved by the physical adsorption of the gas on high-surface-area solids in which the large surface area results from the creation of very fine surface porosity through surface activation methods using, for example, steam, oxygen or CO_2. Some naturally occurring materials (e.g., zeolites) have high surface areas and efficiently adsorb some gases. Adsorption capacities and kinetics are governed by numerous factors including adsorbent pore size, pore volume, surface area, and affinity of the adsorbed gas for the adsorbent.

Low-Temperature Distillation

Low-temperature distillation is widely used commercially for the liquefaction and purification of CO_2 from high-purity streams (typically a stream with >90% CO_2). In low-temperature distillation, a low-boiling-point liquid is purified by evaporating and subsequently condensing it. Low-temperature distillation enables direct production of liquid CO_2 that can be stored or sequestered at high pressure via liquid pumping.

Gas Separation Membranes

Diffusion mechanisms in membranes are numerous and differ greatly depending on the type of membrane used. Generally, gas separation is accomplished via some interaction between the membrane and the gas being separated. For example, polymeric membranes transport gases via a solution-diffusion mechanism (i.e., the gas is dissolved in the membrane and transported through the membrane by a diffusion process).

Inorganic membranes, metallic or ceramic, are particularly attractive because of the many transport mechanisms that can be used to maximize the separation factor for various gas separations. In addition, inorganic membranes can be operated at high pressures and temperatures and in corrosive environments.

Ocean Sequestration

CO_2 is soluble in ocean water, and through natural processes the oceans both absorb and emit huge amounts of CO_2 into the atmosphere.

It is widely believed that the oceans will eventually absorb most of the CO_2 in the atmosphere. However, the kinetics of ocean uptake are unacceptably slow, causing a peak atmospheric CO_2 concentration of several hundred years. The program will explore options for speeding up the natural processes by which the oceans absorb CO_2 and for injecting CO_2 directly into the deep ocean.

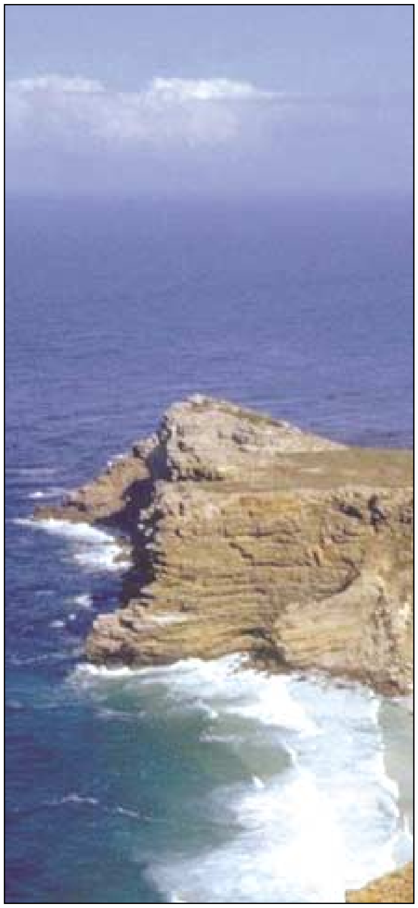
Every year the ocean actively takes up one-third of our anthropogenic CO_2 emissions. Eventually (over 1,000 years), about 85 percent of today's anthropogenic emissions of CO_2 will be transferred to the ocean. Ocean sequestration strategies attempt to speed up this ongoing process to reduce both peak atmospheric CO_2 concentrations and their rate of increase.

Enhancement of Natural Carbon Sequestration

One approach to enhancing the rate of CO_2 absorption in the ocean involves adding combinations of micronutrients and macronutrients to those ocean surface waters deficient in such nutrients. The objective is to stimulate the growth of phytoplankton, which are expected to consume greater amounts of carbon dioxide. When carbon is thus removed from the ocean surface waters, it is ultimately replaced by CO_2 drawn from the atmosphere. The extent to which the carbon from this increased biological activity is sequestered is unknown at this point, and would require additional research. Any R&D on natural enhancement would also require complete examination of potential environmental issues.

Direct Injection of CO_2

Technology exists for the direct injection of CO_2 into deep areas of the ocean; however, the knowledge base is not adequate to optimize the costs, determine the effectiveness of the sequestration, and understand the resulting changes in the biogeochemical cycles of the ocean. To assure environmental acceptability, developing a better understanding of the ecological impacts of both ocean fertilization and direct injection of CO_2 into the deep ocean is a primary focus of this program element. It is known that small changes in biogeochemical cycles may have large consequences, many of which are secondary and difficult to predict. Of particular concern is the effect of CO_2 on the acidity of ocean water.



Sequestration in Geologic Formations

CO_2 sequestration in geologic formations includes oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.

Oil and Gas Reservoirs

In some cases, production from an oil or natural gas reservoir can be enhanced by pumping CO_2 gas into the reservoir to push out the product, which is called enhanced oil recovery (EOR). The United States is the world leader in EOR technology, using about 32 million tons of CO_2 per year for this purpose. From the perspective of the sequestration program, EOR represents an opportunity to sequester carbon at low net cost, due to the increased revenues from recovered oil/gas. In an EOR application, the integrity of the CO_2 that remains in the reservoir is well understood and very high, as long as the original pressure of the reservoir is not exceeded. The scope of this EOR application is currently economically limited to point sources of CO_2 emissions that are near an oil or natural gas reservoir.

Coal Bed Methane

Coal beds typically contain large amounts of methane-rich gas that is adsorbed onto the surface of the coal. The current practice for recovering coal-bed methane (CBM) gas is to depressurize the bed, usually by pumping water out of the reservoir. An additional approach is to inject carbon dioxide gas into the bed. Tests have shown that CO_2 is roughly twice as adsorbing on coal as methane, giving it the potential to efficiently displace methane and remain sequestered in the bed. Carbon dioxide recovery of CBM has been demonstrated in limited field tests, but much more work is necessary to understand and optimize the process.

Similar to the by-product value gained from EOR, the recovered methane provides a value-added revenue stream to the carbon sequestration process, creating a low net cost option. The U.S. coal resources are estimated at 6 trillion tons, and 90 percent of it is unmineable due to seam thickness, depth, and structural integrity. Another promising aspect of CO_2 sequestration in coal beds is that many of the large unmineable coal seams are near electricity generation facilities that are large point sources of CO_2 gas. Thus, limited pipeline transport of CO_2 gas would be required. Integration of coal-bed methane with a coal-fired electricity generation system can provide an option for additional power generation with low emissions.

Saline Formations

Sequestration of CO_2 in deep saline formations does not produce value-added by-products, but it has other advantages. First, the estimated carbon storage capacity of saline formations in the U.S. is large, making them a viable long-term solution. It has been estimated that deep saline formations in the U.S. could potentially store up to 500 billion metric tons of CO_2. Second, most existing large CO_2 point sources are within easy access to a saline formation injection point, and therefore sequestration in saline formations is compatible with a strategy of transforming large portions of the existing U.S. energy and industrial assets to near-zero carbon emissions via low-cost carbon sequestration retrofits.

Assuring the environmental acceptability and safety of CO_2 storage in saline formations is a key component of this program element. Determining that CO_2 will not escape from formations and either migrate up to the earth's surface or contaminate drinking water supplies is a key aspect of sequestration research. Although much work is needed to better understand and characterize sequestration of CO_2 in deep saline formations, a significant baseline of information and experience exists. For example, as part of EOR operations, the oil industry routinely injects brines from the recovered oil into saline reservoirs, and the U.S. Environmental Protection Agency (EPA) has permitted some hazardous waste disposal sites that inject liquid wastes into deep saline formations.

The Norwegian oil company, Statoil, is injecting approximately one million metric tons per year of recovered CO_2 into the Utsira Sand, a saline formation under the sea associated with the Sleipner West Heimdel gas reservoir. The amount being sequestered is equivalent to the output of a 150-MW coal-fired power plant. This is the only commercial CO_2 geological sequestration facility in the world.

Sequestration in Terrestrial Ecosystems

Carbon sequestration in terrestrial ecosystems is either the net removal of CO_2 from the atmosphere or the prevention of CO_2 net emissions from the terrestrial ecosystems into the atmosphere.

Enhancing the natural processes that remove CO_2 from the atmosphere is thought to be one of the most cost-effective means of reducing atmospheric levels of CO_2, and forestation and deforestation abatement efforts are already under way.

The terrestrial biosphere is estimated to sequester large amounts of carbon (approximately 2 billion metric ton of carbon per year). R&D in this program area seeks to increase this rate while properly considering all the ecological, social, and economic implications. There are two fundamental approaches to sequestering carbon in terrestrial ecosystems: (1) protection of ecosystems that store carbon so that sequestration can be maintained or increased; and (2) manipulation of ecosystems to increase carbon sequestration beyond current conditions.

This program area is focused on integrating measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmland and forests, with fossil fuel production and use. The following ecosystems offer significant opportunity for carbon sequestration:

- *Forest lands.* The focus includes below-ground carbon and long-term management and utilization of standing stocks, understory, ground cover, and litter.
- *Agricultural lands.* The focus includes crop lands, grasslands, and range lands, with emphasis on increasing long-lived soil carbon.
- *Biomass croplands.* As a complement to ongoing efforts related to biofuels, the focus is on long-term increases in soil carbon.
- *Deserts and degraded lands.* Restoration of degraded lands offers significant benefits and carbon sequestration potential in both below- and above-ground systems.
- *Boreal wetlands and peatlands.* The focus includes management of soil carbon pools and perhaps limited conversion to forest or grassland vegetation where ecologically acceptable.

The program area is being conducted in collaboration with DOE's Office of Science and the U.S. Forest Service of the U.S. Department of Agriculture.

Advanced Concepts/Modeling and Assessments

Advanced Chemical and Biological Approaches

Recycling or reuse of CO_2 from energy systems would be an attractive alternative to storage of CO_2. The goal of this program area is to reduce the cost and energy required to chemically and/or biologically convert CO_2 into either commercial products that are inert and long-lived or stable solid compounds.

Two promising chemical pathways are magnesium carbonate and CO_2 clathrate, an ice-like material. Both provide quantum increases in volume density compared to gaseous CO_2. As an example of the potential of chemical pathways, the entire global emissions of carbon in 1990 could be contained as magnesium carbonate in a space 10 km by 10 km by 150 m.

Concerning biological systems, incremental enhancements to the carbon uptake of photosynthetic systems could have a significant positive effect. Also, harnessing naturally occurring, non-photosynthetic microbiological processes capable of converting CO_2 into useful forms, such as methane and acetate, could represent a technology breakthrough. An important advantage of biological systems is that they do not require pure CO_2 and do not incur costs for separation, capture, and compression of CO_2 gas. This program area will seek to develop novel and advanced concepts for capture, reuse, and storage of CO_2 from energy production and utilization systems based on, but not limited to:

- Biological systems;
- Advanced catalysts for CO_2 or CO conversion;
- Novel solvents, sorbents, membranes and thin films for gas separation;
- Engineered photosynthesis systems;
- Non-photosynthetic mechanisms for CO_2 fixation (methanogenesis and acetogenesis);
- Genetic manipulation of agricultural and tree to enhance CO_2 sequestering potential;
- Advanced decarbonization systems; and
- Biomimetic systems.

Sequestration Modeling and Assessments

Better assessments of the costs, risks, and the potential of carbon sequestration technology are essential to develop technological options for greenhouse gas mitigation.

Sound assessment capabilities are required to evaluate technological options in a total systems context, considering costs and impacts over a full product cycle, and societal and environmental effects to provide a basis for assessing trade-offs between local environmental impacts and global impacts. Analytical tools are needed to strategically select the most promising R&D efforts that have high potential, but significant uncertainties, associated with their costs and effectiveness.

Some of the projects in this cross-cutting activity include:

- Adapt existing oil and gas reservoir models used for fossil fuel production to carbon sequestration;
- Develop risk assessment models and life-time prediction models for geologic and ocean sequestration;
- Assess the capacities of geologic and ocean storage sites;
- Provide verification for the sequestration capabilities of various technological options;
- Develop criteria to guide selection of potential storage sites, including enhancing natural sinks; and permit uniform assessments of the carbon mitigation potential of novel and advanced systems; and
- Model naturally occurring CO_2 formations and processes to yield information that could serve as analogs for estimating the long-term CO_2 storage potential of depleted oil and gas reservoirs, and other approaches.

National Lab Participation in CO_2 Sequestration

As part of DOE's project selections in 2000, the Department is providing funds to the National Laboratories over the next three years to study sequestration innovations ranging from carbon dioxide filtering membranes to the development of "biofilms" made up of carbon converting microorganisms.

In seven of the eight projects selected, lab researchers are teaming with scientists from the private sector, universities, or other agencies. The National Laboratory projects are:

- **Los Alamos National Laboratory and Idaho National Engineering and Environmental Laboratory** will collaborate with the University of Colorado, Pall Corporation, and Shell Oil Company in a three-year project to develop an improved high-temperature polymer membrane for separating CO_2 from methane and nitrogen gas streams.
- **Sandia and Los Alamos National Laboratories** will join with Strata Production Company and the New Mexico Petroleum Recovery Research Center in a three-year study of ways to inject CO_2 into depleted oil reservoirs.
- **Lawrence Berkeley, Lawrence Livermore, and Oak Ridge National Laboratories** will cooperate with Chevron, Texaco, Pan Canadian Resources, Shell CO_2 Company, BP Amoco, Statoil, and the Alberta Research Council Consortium in a three-year study of geologic sequestration of carbon dioxide in formations such as brine reservoirs, depleted oil reservoirs, and coal beds.
- **Idaho National Engineering and Environmental Laboratory** will team with Purdue University, Pacific Gas and Electric, Southern California Gas, and BP Amoco to develop a novel "gas-liquid contactor" that creates a whirlwind-like vortex for separating CO_2 from natural gas and flue gas.
- **Argonne National Laboratory** will conduct a two-year study of ways to retrofit a coal power plant with recirculating technology to concentrate carbon dioxide sufficiently to transport it to sequestration sites.
- **Lawrence Livermore National Laboratory** will team with the U.S. Geological Survey and Monterey Bay Aquarium Research Institute in a two-year study of ice-like hydrates that form when cold CO_2 is pumped into deep ocean basins.
- **Oak Ridge National and Pacific Northwest National Laboratories** will join with Ohio State University and Virginia Polytechnic Institute in a two-year project to study the use of soil enhancers made from the solid wastes of coal plants, paper mills, and sewage treatment facilities to improve the natural carbon uptake of lands disturbed by mining, highway construction, or poor management practices.
- **Idaho National Engineering and Environmental Laboratory** will team with Montana State University and the University of Memphis in a two-year study of ways to grow microorganisms known as cyanobacteria as "biofilms" that could capture and convert carbon dioxide through photosynthesis.

In Partnership with Industry

CO_2 Capture and Geologic Sequestration: Progress through Partnerships was a collaborative workshop held in September 1999 to create new solutions to the challenge of CO_2 capture and geologic sequestration. The workshop was jointly sponsored by BP Amoco, DOE's Office of Fossil Energy, and the International Energy Agency's Greenhouse Gas R&D Programme (IEA/GHG). The workshop consisted of: (1) international, national, and industry perspectives on sequestration; (2) panel discussions on CO_2 capture and geologic sequestration technologies; (3) status reports from ongoing CO_2 sequestration projects; and (4) working sessions to develop an industry work program leading to breakthroughs in costs and performance.

The partnership between BP Amoco, DOE, and the IEA/GHG was successful in bringing together a diverse group of experts, with over 140 participants attending the conference. Seventy-five percent of the participants were from industry, with 30 percent of them coming from outside the United States.

BP Amoco will use the information and contacts from the workshop to help its efforts to form a Joint Implementation Project that sequesters CO_2 in Alaska's North Slope. The federal government and IEA will apply the information from the workshop to the management of their R&D activities. Additional information including a summary of the workshop findings can be found on the NETL website at www.netl.doe.gov.

BP Amoco and Alaska's North Slope

The opportunity on Alaska's North Slope stems from the fact that a number of large point sources of CO_2 emission are located near a large, undeveloped viscous oil reservoir. The concept is to capture the CO_2 from the point sources and inject it into the viscous oil reservoir where it will decrease the viscosity of the oil, thus increasing the productivity of the wells to the point where they are economical to operate. The potential scale of sequestration is large, 2–4 million metric tons of CO_2 sequestered per year against 9.1 million metric tons of CO_2 emitted per year.

BP Amoco, together with the National Laboratories and DOE, are investigating cost reductions to geologic sequestration. Based on current technology, the North Slope sequestration is not economical on its own merits. To improve project economics, BP Amoco is seeking to: (1) reduce the cost of CO_2 capture and gas treatment plants; (2) increase sequestration efficiency and EOR recovery; and (3) utilize economies of scale from broad application.

Given that BP Amoco is committed to reducing CO_2 emissions by 30 million metric tons per year by 2010, sequestration may be attractive compared to other options for emissions reductions. Meeting the goal of commercial-scale operation by 2010, BP Amoco is looking toward completion of the necessary technology development by 2002–2003 and pilot-scale demonstration by 2006.